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Laser-Produced X-UV Spectra of Ta and W

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Spectra of tantalum and tungsten in the 15-100 A region were obtained with a focused Nd: glass laser source coupled to a 600 line/mm grazing-incidence grating spectrograph. The spectral lines were identified as transitions to the 4p subshell.

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LASER-PRODUCED X-UV SPECTRA OF Ta and W*

Introduction

High-Z refractory metals including tungsten are being used as limiters in Tokamak devices such as the PLT at Princteon University[1] and the ORMAK at Oak Ridge National Laboratory.[2] Significant work has been devoted to the spectroscopic study of impurities such as O, Fe, and Mo in the ST Tokamak at Princeton[3,4] and the TFR Tokamak in France.[5,6] X-UV spectroscopy of highly-ionized W is needed in order to measure the concentration of this element in the PLT or other devices in which this element or other similar high-Z elements are present as impurities. Low intensities and spectral complexities complicate identification of lines directly from the Tokamak plasma data. Therefore, spectroscopy using other sources with high electron temperatures is necessary to distinguish the most intense spectral lines for highly-ionized atoms. Spectral identifications in high-Z elements can be achieved from data produced by focused-laser beams on pure elemental targets, as has been demonstrated at the Naval Research Laboratory (NRL).[7-9]

Experimental

Beams from the high-powered Nd:glass laser system at NRL were focused onto planar targets of Ta and W. The targets were viewed by a McPherson Model 247, 2.2 m instrument and a gold-coated 600 line/mm Baush and Lomb 1° 30' blazed grating at 88° incidence. The spectra were recorded photographically on Kodak 101-05 plates through a 10 μm entrance slit. The grating entrance slit was placed 90° to the incident beam which was focused with a f/1.9 aspheric lens. The spectra were collected in the 15 to 100 A region with three and five shots on the Ta and W targets, respectively. The 100 psec duration shots were roughly at the 10 J level. Underexposed plates resulted, that is, the Ta and W lines were barely readable. Shortly after collecting these data the laser facility was shut down for a new beam installation without opportunity to repeat the experiment.

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Results

The pair of Ta and W plates were examined and found to consist of moderately intense C and O lines and absorption edges, together with weak but distinct lines believed to be from the metals under investigation. Calibration at the $\pm$ 20 mA level was provided by known wavelengths[10] of O VII and C V and C VI lines in first and second orders from 21.6 to 80.5 A. Both plates had a broad intense continuum whose intensity maximum occurred at $\sim$ 50 A. Most of the unknown lines were found in two groupings at roughly 50 and 65 A superimposed on the continuum distribution, as shown on the densitometer trace of the Ta plate in figure 1.

Preliminary calculations with a Dirac-Slater code[11] indicated that the observed lines could occur for either 4d-4f transitions in Pd I-like W XXIX or for 4p-4d transitions in Kr I-like W XXXIX. A plot of the number of electrons removed in tungsten versus plasma electron temperature based on a coronal model code[12] is shown in figure 2. Examination of the curve reveals the absence of any plateaus where the degree of electron stripping is constant over a temperature range. Therefore, the plasma temperature distribution will result in a range of ionization states, and blending of spectral lines might be anticipated for the above mentioned transitions. The coronal electron temperatures corresponding to the above states in tungsten are in the energy range of 150-400 eV and 400-700 eV, respectively. Since plasma temperatures as high as 700 eV have been obtained under similar laser conditions using the same short-focal-length lens, the higher stage of ionization was choosen for more extensive calculations; however the plasma temperature was not determined in this experiment. Calculations for transitions for the Kr I-like and neighboring ionization states were made by one of us (R.D.C.) using Hartree-Fock wavefunctions corrected for relativistic effects in an ab initio atomic structure code.[13] The accuracy of this code is estimated to be 0.1% for $\Delta n \neq 0$ transitions and 1% for $\Delta n = 0$ transitions.

The wavelengths measured for X-UV lines for Ta and W in highly stripped states are listed in Table I. Because the lines were weak and superimposed on an intense continuum, only approximate intensity estimates could be made. In Table II are the calculated transition wavelengths for the 4p-4d and 4p-5s lines in Kr I-like Ta and W together with the range of wavelengths for the most intense lines in the next two higher stages of ionization.

Several results can be gained from comparing the experimental and calculated wavelengths. The line measured at 18.452 ± 0.020 A in the tungsten spectrum agrees within experimental error with the calculated $4p^6$-$4p^5$ $(^2P_{3/2})5s$ line in W XXXIX at 18.468 A. By coincidence the experimental and computational uncertainties are both at the 0.1% level for this transition. Unfortunately this same transition was not observable because of weak intensity in the Ta spectrum nor was the $^2P_{1/2}$ transition observable in either spectrum. The grouping of experimental lines between 63.7 and 67.0 A in Ta and 60.6-65.4 A in W agreed well with the predicted intense lines for the $4p^6$-$4p^5(^2P_{3/2})$, $4d(^2D_{5/2})$ transitions in Kr-like ions and also for transitions in Br- and Se-like ionization states for both elements. The group of experimental lines between 50.0 and 51.8 A in Ta is about 3% longer in wavelength than the calculated group of transitions for Br- and Se-like ions. The occurrence of experimental lines in both Ta and W for the $4p^6$-$4p^5(^2P_{1/2})$, $4d(^2D_{3/2})$ transition may be coincidential. It is noteworthy that the intensities of continuum in the Ta spectrum near 50 and 65 A were roughly in a 2:1 ratio corresponding to an approximate ratio of oscillator strengths for the three ionization states. The continuum patterns observed in the Ta and W plates were unique and not present in C or Fe spectra collected in experiments with exploding wire plasma sources using the same spectrograph. Line blending to form continua was observed in exploded-tungsten-wire spectrum.[14]

Conclusion

Weak lines superimposed on continua were observed in the Ta and W spectra which were not inconsistent with calculated wavelengths for transitions in highly ionized atoms. The atomic structure calculations indicate that excitation into the 4p subshell produces overlapping groups of transitions, which with low resolution would result in continua peaks. Further experimental work is indicated with higher resolution and at coronal temperatures near 800 eV in order to excite and identify the simpler spectra with 4s or single 4p electron vacancies.

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TABLE I.

Element Ta

Experimental Wavelengths, A	Intensity Above Continuum	Impurity
40.268 ± .020	550	C V
48.293	weak	
48.376	"	
48.442	"	
48.509	"	
49.238	"	
49.599	"	
49.875	"	
50.002	56	
50.467	16	
50.754	88	
51.375	103	
51.888	13	
52.803	26	
54.166	weak	
54.498	"	
55.409	26	
55.771	30	
56.268	59	
56.394	weak	
56.933	101	C VI[2]
62.431	46	
63.585	66	
63.612	51	
63.698	99	
64.806	57	
65.220	31	
65.354	100	
65.483	239	
66.724	82	
66.990	69	
67.472	235	C VI[2]

Table I (Continued)

Element W

Experimental Wavelengths, A	Intensity Above Continuum	Impurity
18.452 $\pm$ .020	weak	
40.268	290	C V
46.446	weak	
49.1	"	
*		
56.932	28	C VI^2
60.600	39	
61.939	19	
62.355	32	
62.419	38	
63.480	19	
64.280	weak	
64.389	"	
64.347	"	
67.472	90	
80.536	76	C V^2
82.543	weak	

*A plate defect extended from 49.3 to 53.5 A.

TABLE II. Theoretical Calculations

Ionization State	Sequence	Calculated Wave Length (A)	gf	Classification in jj Coupling
Ta XXXVIII	Kr I	84.336	0.01	$4p^6-[4p^5(^2P_{3/2}),4d(^2D_{3/2})]_1$
		66.351	1.33	$-[4p^5(^2P_{3/2}),4d(^2D_{5/2})]_1$
		48.378	2.61	$-[4p^5(^2P_{1/2}),4d(^2D_{3/2})]_1$
		19.237	0.43	$-[4p^5(^2P_{3/2}),5s]_1$
		16.907	0.26	$-[4p^5(^2P_{1/2}),5s]_1$
Ta XXIX	Br I	64.7-68.3		
		48.4-49.8		
Ta XL	Se I	65.2-69.0		
		48.5-49.4		

Table II. (Continued)

Ionization State	Sequence	Calculated Wave Length (A)	gf	Classification in jj Coupling
W XXXIX	Kr I	82.507	0.01	$4p^6-[4p^5(^2P_{3/2}),4d(^2D_{3/2})]_1$
		64.541	1.35	$-[4p^5(^2P_{3/2}),4d(^2D_{5/2})]_1$
		46.496	2.54	$-[4p^5(^2P_{1/2}),4d(^2D_{3/2})]_1$
		18.468	0.43	$-[4p^5(^2P_{3/2}),5s]_1$
		16.160	0.26	$-[4p^5(^2P_{1/2}),5s]_1$
W XL	Br I	63.0-66.5		
		46.4-47.6		
W XLI	Se I	63.5-67.2		
		46.6-47.6		

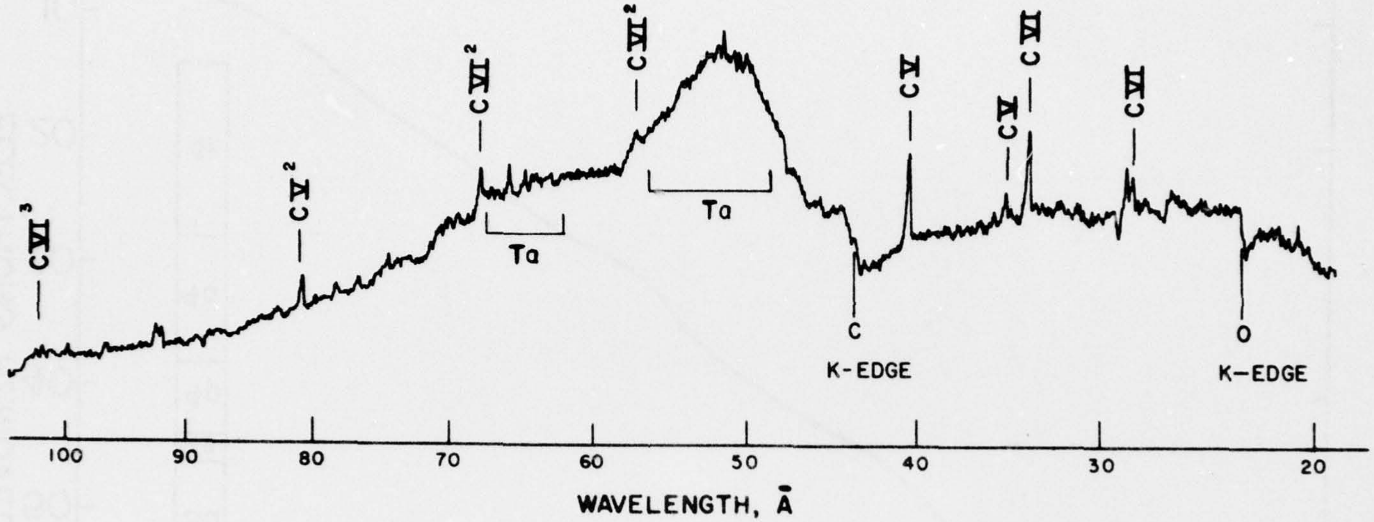

Fig. 1 — Densitometer trace of a laser-produced Ta spectrum in X-UV region

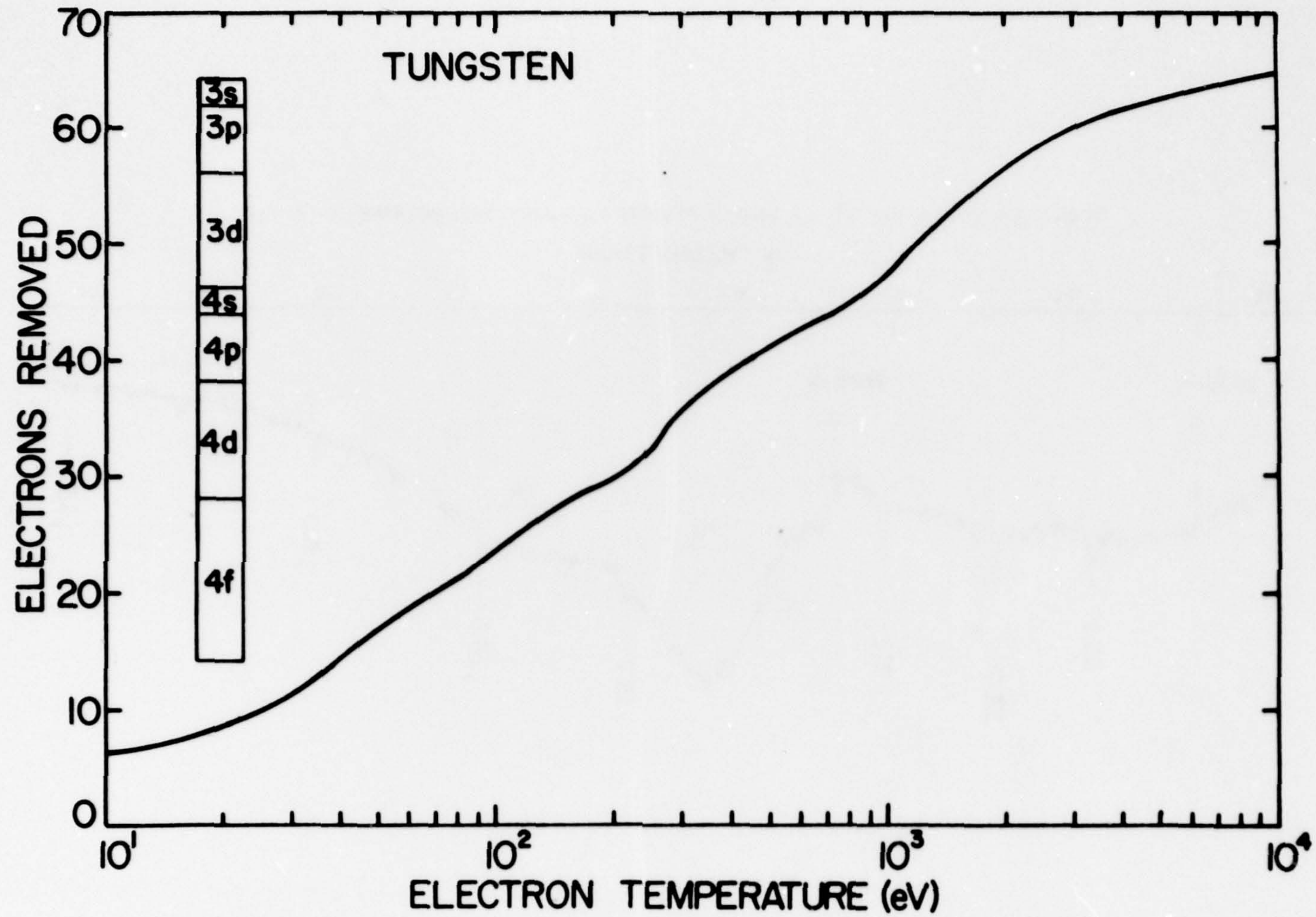

Fig. 2 — Number of electrons removed in W versus plasma electron temperature based on coronal model calculations. The corresponding shell structure is shown in the boxes on the left.